OVERVIEW OF THE RFX-mod FUSION SCIENCE PROGRAM

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Abstract. The RFX-mod fusion science program has made significant progress since the last 2010 IAEA Fusion Energy Conference. The activities focused on the goal of exploring the fusion potential of the RFP magnetic configuration and that of contributing to the solution of key science and technology problems in the roadmap to ITER. Active control of several plasma parameters has been a key tool in this program. New upgrades on the system for active control of MHD stability are under way and will be presented here. Unique in the portfolio of existing fusion devices, RFX-mod has been operated both as a RFP and as a tokamak. The latter operation has allowed the exploration of $q_{95} < 2$ with active control of MHD stability and studies concerning basic energy and flow transport mechanisms. Strong interaction has continued with the stellarator community in particular on the physics of helical states.

1. RFX mission and highlights.
With a program well-balanced among the goal of exploring the fusion potential of the reversed field pinch (RFP) magnetic configuration and that of contributing to the solution of key science and technology problems in the roadmap to ITER, the European RFX-mod device [1] has produced a set of high-quality results since the last 2010 Fusion Energy Conference. Key words of the RFX-mod fusion science program are integration and flexibility: RFX-mod is in fact a device where studies on all the three major fusion magnetic configurations are performed. RFX-mod is a 2 MA RFP device (2 m and 0.46 m major and minor radii respectively, for a 9 m$^3$ plasma), and is performing the largest part of its experimental program as an RFP. But RFX-mod can also be operated as a 150 kA tokamak and its RFP advanced confinement helical states have 3D features that are studied with stellarator tools. Following the discovery of the Single Helical Axis (SHAx) states at high plasma current, with improved confinement, reported at the last FEC [1] a robust experimental program dedicated to their optimization has progressed and is leading to significant improvement of density and MHD stability control. This program has laid the foundation for stationary helical states at higher density. Modelling and theoretical work is better characterizing the equilibrium, stability and transport properties of these states – with the added value of a growing synergy with the broader fusion community on the use and benchmark of codes for three-dimensional fusion physics. The RFP is a main actor of the three-dimensional fusion physics effort. Feedback control science is one of the RFX fusion science flagship and has been developed not only to further optimize RFX performance, but also to provide key contributions to the ITER and tokamak control program. In addition to RFP physics, a strong experimental tokamak program has started (and will further develop in the future): its main goals are to directly address feedback issues in the tokamak configuration and to provide results on basic turbulence driven transport mechanisms and on edge physics.

The paper is organized as follows: Section 2 briefly recalls what is an RFP, while the main results of the high current operation in RFX-mod configuration are reported in Section 3. Section 4 summarizes the progress in the 3D modelling of the RFP magnetic equilibrium, and in Section 5 highlights of theory and modelling non-linear MHD studies are given. In Section 6 recent results from transport characterization in helical states are discussed. Section 7 covers RWM physics and control studies. Section 8 summarizes the main achievements when RFX is operated as a Tokamak. Section 9 gives a short description of the feedback control system upgrade presently in the test phase, and finally concluding remarks and outlook are presented in Section 10.

2. The Reversed Field Pinch in a nutshell.
The RFP magnetic configuration belongs to the class of toroidal pinches. As the tokamak, the RFP carries toroidal plasma current and is confined by an equilibrium magnetic field whose
main components are toroidal and poloidal. Different from the tokamak, they are of comparable amplitude. Therefore the RFP confines the same plasma current with an average toroidal field, which is a factor of ten smaller than in a tokamak. Moreover the magnetic field at the coils is very small, thus leading to high engineering beta and to low stress in the coils. The toroidal field produced by external coils is indeed small, of the order of some mT for MA plasmas, since the field is mainly produced, through a self-organization process, by currents flowing in the plasma. In RFX-mod at plasma current $I_p > 1$ MA the magnetic equilibrium becomes helical and the plasma self-organizes in the Quasi Single Helicity (QSH) state. In this state the broad spectrum of tearing modes (TM), which characterize the standard Multiple Helicity (MH) condition condenses in an almost monochromatic spectrum peaked around a dominant helicity $(m=1,n=-7)$. At $I_p > 1$-1.2 MA self-organization can proceed up to the point where the magnetic axis becomes helical and the plasma enters the Single Helical Axis (SHAx) state [2]. In the SHAx state the core of the equilibrium is helical, while the edge is almost axisymmetric, as shown in Fig. 1. Inside the helical structure the energy and particle confinement is enhanced and electron temperatures exceeding 1 keV are measured, with steep gradients in the profile, signature of internal transport barriers and magnetic chaos reduction.

3. Development of high plasma current RFP scenarios

3.1 Active control exploited and advanced in RFX

The exploration of the plasma current regime above 1 MA is a key charge for RFX-mod, which is the only RFP device capable to achieve plasma current up to 2 MA. This is important since the RFP is a purely ohmic heated configuration and its confinement increases with plasma current [1]. The assessment of the fusion perspectives of the RFP configuration requires therefore a careful exploration of the multi-MA regime.

In this effort RFX-mod benefits from several systems to control key plasma quantities: they not only allow to improve RFP performance, but also to contribute to a key topic for fusion as that of active control. The front-runner of RFX control is the system for active control of MHD stability, made by 192 active coils, each independently driven [3]. The high-current experimental program progressed in the last two years along three main lines of action, all based on control:

a) Density control In RFX-mod, the carbon wall, due to its high Hydrogen retention, dominates the behaviour of the plasma density, leading to uncontrolled H release in presence of strong Plasma Wall Interaction (PWI). Experiments testing several techniques of wall lithization led to reduce the recycling and improve density control [4] (Section 3.2).

b) Feedback control of MHD stability. This is key to provide the smooth magnetic boundary, which is necessary to achieve the helical states. A primary activity has been the improvement and full exploitation of such system [5] (Section 3.3).

c) Magnetic equilibrium control. The magnetic equilibrium influences the quality of helical states and successful optimization experiments have been performed (Section 3.4).

3.2 Plasma-wall interaction and density control.

RFX-mod, as all present RFPs, has not a divertor and operates in a limiter configuration. Its first wall is covered by graphite tiles. This guarantees significant experimental flexibility since graphite can withstand localized thermal loads up to tens of MW/m$^2$, which may happen when new scenarios are explored and still not optimized. As plasma facing material, Carbon has the additional advantage of maintaining low plasma contamination ($Z_{eff}=2$ at $n/n_G=0.15$, with $n_G=I_p/\pi a^2$ being the Greenwald density). A drawback is that the high H retention of graphite makes the density control difficult to achieve, ultimately limiting the plasma performance and preventing the development of the QSH states for $n/n_G>0.3$. The equilibrium density is in fact independent on the amount of feeding particles. To improve density control and to contribute to the worldwide research on plasma facing components, a lithization
program has been recently started, in addition to more traditional wall-conditioning techniques such as Glow Discharge Cleaning and Boronization [4]. Lithium wall conditioning has been applied by evaporation with a Liquid Lithium Limiter [6] and with single pellet injection [7]. Pellets injected about an overall amount of 1 g of Li, while the total amount of evaporated Li in the first campaign is about 14 g. Significant improvement of the density control is observed. Gas puffing or H-pellet can effectively control density without being dominated by the wall recycling, which is significantly reduced. A clear signature comes from H influx that, especially at high density, is lower in presence of wall lithization. Fig. 2 shows a discharge with Li coating: plasma density is well correlated with the gas puffing pulses. The improved density control with Li-coated wall gives access to high-density high-plasma current ($I_p > 1.5$MA) scenarios up to $n/n_G \approx 0.5$. QSH states develop up to $n/n_G \approx 0.35$. With lithization edge density is lower, while edge temperature is higher. However, the effect on core profiles is at the moment small. This can have several causes. First, measurements of Li influxes at different toroidal positions show that the evaporation is presently effective in covering the wall for less than one half of the machine surface. In addition, in RFX-mod the core fuelling is insufficient, consisting of 8 H pellets during the whole discharge lasting about 0.5 sec, with a particle confinement time <10 msec. Therefore, the plasma fuelling must anyway come from the wall, and increasing density leads to edge peaked profiles. To impact the global confinement as observed in other devices [8-11] it appears necessary to improve the uniformity of the Li layer and the efficiency of the core fuelling. An action for a more uniform coating, with a significant amount of injected Li, has been done testing a multipellet injector developed at PPPL [4]. It allows the injection of Li spheres of 0.8-1mm diameter with a frequency up to 200Hz. A first positive test of the equipment has been done in RFX-mod.

### 3.3 Optimization of feedback control of MHD stability.

The 192 active coil system has recently been a powerful tool to control MHD stability (see [12] for a recent review) and to tailor the edge magnetic boundary conditions (topics where the RFP community is very active [13]). The latter, in particular, is an example on how three-dimensional magnetic fields play a role in improving plasma stability and confinement properties, as described for example in [14]. Recent experiments on MHD feedback control tackled difficult and important issues, common to all configurations using MHD feedback control including large tokamaks.

#### 3.3.1 Externally applied 3D magnetic field

Experimentally, QSH states are not completely stationary and occasional back-transitions to MH states are observed [1]. To achieve steady state helical RFP equilibria, with robustly controlled amplitude and phase, external 3D boundary conditions are applied through magnetic feedback, as suggested in [15]. This control scheme, previously applied at lower
currents [16], has been extended to high current, \( I_p > 1.5 \) MA. Unless high amplitude helical components are applied, back-transitions are still observed (see Fig. 3), though with the dominant mode remaining higher than the secondary ones. However, such externally applied fields have the positive effect to stimulate helical states in otherwise inaccessible parameter ranges, such as at high plasma density, as shown in Fig. 3 where the application of helical magnetic boundary conditions with \( m=1, n=-7 \) (shadowed region) induces QSH up to a Greenwald fraction \( n/n_{GW} \approx 0.5 \). During this operation the plasma \( \beta \) increases, due to the increasing density. At \( n/n_{GW} \leq 0.2 \) electron internal transport barriers similar to those observed in spontaneous helical states are observed also in presence of externally applied helical fields. Stationary QSH states are instead achieved when a non-resonant perturbation is applied (see Sec.5).

### 3.3.2 Modal dynamic decoupler

A general problem for MHD stability feedback control derives from unavoidable three-dimensional structures in the magnetic front-end, like gaps and portholes in the vacuum vessel. Their dynamic response to externally applied magnetic field distorts the feedback action and induces unwanted magnetic field errors that are not completely cancelled by the standard feedback laws. This happens not only for the RFP, but anytime a magnetic field is applied to the plasma.

In RFX-mod a modal dynamic decoupler, dealing with couplings between the spatial Fourier components of the signals from the sensors and of the actuator currents, has been developed \([5,17,18]\). The elements of the transfer matrix which links the currents in the coils with the radial magnetic field they produce are evaluated in different ways, including the use of the finite elements electromagnetic code CARIDDI \([17,19]\). The effect of the real-time implementation of the modal dynamic pseudo-decoupler is shown in Fig. 4. A clear reduction of the edge error field harmonics is observed.

### 3.3.3 New feedback variable

To further improve the control of tearing modes, a modal feedback variable with different weights of the radial and of the toroidal component \([20]\) has been tested, first with predictive numerical simulations and then with experiments. The expected advantage is that the latency would decrease if the toroidal field measurements would be no longer necessary. Simulations \([21]\) show that the qualitative dependence of the tearing mode edge radial field on the proportional gain for the new variable is similar to the standard case. Experiments show no significant difference in the edge radial field reduction between the two options, but further work is in progress to fully exploit the new scheme.

### 3.4 Axisymmetric magnetic equilibrium optimization

A complementary approach to improve the performance of helical state relies on the control of the axisymmetric component of the equilibrium magnetic field. At the highest currents the best plasma performances with SHAx states have been achieved with shallow reversal of the edge toroidal field. This is shown in Fig. 5-A, where the amplitude of the dominant mode increases as the reversal parameter \( F_B = B_B(a)/<B_B> \) approaches 0. The null point of the \( q \) shear, corresponding to the barrier foot in SHAx regimes \([22]\), moves towards the edge at shallow reversal. This increases the volume
4. Three-dimensional modelling of magnetic equilibrium

The intrinsic helical nature of the equilibrium reached when RFX-mod approaches the Single Helicity RFP state has a strong similarity with the Stellarator topology and establishes a robust bridge between the two communities. In particular, the use of equilibrium and transport analysis codes developed for the Stellarator has been successfully applied to the RFP. The Stellarator equilibrium codes VMEC [24] and V3FIT [25] have been adapted to reconstruct RFX-mod equilibria with the inclusion of diagnostics. The addition in V3FIT of other diagnostics providing information on radial profiles in addition to magnetic probes reduces the equilibrium degeneracy. The equilibria so obtained have been successfully used for stability and transport analysis [26,27]. VMEC is the equilibrium solver and V3FIT minimizes the difference between modelled and available experimental signals (magnetic, Thomson scattering, SXR and density measurements). V3FIT iterates adjusting safety factor \( q \) and pressure profiles as well as the shape of the last closed flux surface. As an example Fig. 6 shows the remapping of the electron temperature profile on the equilibrium reconstruction by V3FIT done using as a constraint the experimental pressure profile [28,29].


Significant progress has been done in 3D non-linear MHD modelling of helical states [44]. The Specyl code shows that, starting from a MH chaotic configuration, the system can be driven to a QSH with an externally selected helicity, if the mode amplitude is beyond a threshold (estimated around 2%) [30]. A similar action has been proposed for an experiment in RFX-mod where a magnetic helicity corresponding to a non-resonant Resistive Wall Mode – normally eliminated by feedback control – is instead successfully exploited as a seed of new stationary helical regimes. The transition to the new stationary QSH state occurs in a robust way (Fig. 7). A study on toroidal geometry effects has been started with the PIXIE3D code [31]. Stationary helical RFP equilibria spontaneously develop in toroidal geometry like in the cylindrical one. The main difference between helical states in the cylinder and the torus is the presence of toroidally coupled harmonics in the latter case. These harmonics cause a change in the magnetic topology, with the formation of secondary islands. A \( m=0 \) islands chain with same toroidal periodicity as the helical state is produced at the reversal surface.

6. Confinement and transport in helical states

6.1 Core energy transport

The heat diffusivity profile \( \chi_e \) in the transport barrier region has been evaluated during several QSH cycles by solving the energy transport equation in helical coordinates and using the helical equilibrium calculated by VMEC and the experimental electron temperature profiles
At the barrier location the energy transport improves significantly. $\chi_e$ between 5 and 20 m$^2$s$^{-1}$ is obtained as shown in Fig. 8, where the predictions for $\chi_e$ in the barrier region by the ASTRA transport code [33] are also reported. When the amplitude of the normalized dominant mode is $<4.5\%$, $\chi_e$ is always above 10 m$^2$s$^{-1}$. At high dominant mode amplitude, when the QSH is purer, $\chi_e$ drops to values as low as $\approx 5$ m$^2$s$^{-1}$. These values are well below those typical of the regions outside the helical domain ($\chi_e=40-100$ m$^2$s$^{-1}$), but still larger than the neoclassical estimate $\chi_{e,\text{neo}} \approx 1$ m$^2$s$^{-1}$, indicating that instabilities other than tearing modes may be driving transport. Linear gyrokinetic calculations by the GS2 code show that Micro Tearing (MT) modes, driven by the temperature gradient, may become unstable in the RFP and drive transport. The estimate of the heat diffusivity caused by MT modes $\chi_{\text{MT}}$ leads to the values also drawn in Fig. 8 (red points), of the same order of the experimental ones at the highest amplitude of the dominant mode and may therefore be responsible for a large part of the residual transport in SHAx states. An experimental evidence of the presence of MT modes in RFX-mod helical states has been measured for the first time in a fusion device by the in-vessel system of magnetic probes.

If the transport reduction at the thermal barrier is related to the reduced stochasticity, an open question remains about the transport mechanism in the core, where the temperature profile is flat. Recently, it has been proposed that the magnetic chaos related to the $m=2$ modes could account for the $\chi_e$ values inside the barrier (40-100 m$^2$s$^{-1}$). A model where transport is related to self-consistently generated vortical drift motions due to electrostatic turbulence has also been proposed [34].

To explain transport in helical states, ion temperature gradient (ITG) modes have been studied. Such instabilities are strongly stabilized compared to tokamak plasmas, due to the stronger Landau damping acting in low-$q$ configurations such as the RFP [35]. However, it has been proposed that in the presence of strongly outwardly peaked impurity profiles ITG may be less damped [36]. Quasi-linear and nonlinear 3-species simulations of ITG turbulence prove that the inward impurity flux eventually provided by a strong ITG would not be compatible with the measured positive impurity peaking [37].

Particle transport also is no longer consistent with stochasticity driven by global tearing modes. The experimental electron density profiles, reproduced by the ASTRA code, show that the average value of the particle diffusion coefficient inside the thermal barrier is smaller by a factor 2-5 with respect to the MH regimes.

6.2 Effects of helical deformation at the edge

The effect of non-axisymmetric magnetic perturbation on the plasma edge is important in present fusion research: in particular, in tokamaks resonant and non-resonant magnetic perturbation (RMP) are applied to mitigate ELMs [38,39] or induce edge ergodization [40]. In RFX-mod, a natural non-axisymmetric perturbation is present at the edge, since in QSH states the residual helical ripple modulates the kinetic properties of the plasma [41,42].

Fig. 9 reports the evolution of the H influx, of the electron pressure characteristic length $L_p=(\nabla p_e/p_e)^{-1}$, of the floating potential, of the toroidal flow fluctuation and of the radial electric field as a function of the helical angle defined as $u_{m,n}=m\theta-n\varphi_{m,n}$, where $\varphi_{m,n}$ represents the proper phase of the mode with helicity $(m,n)$. The helical angle represents an effective poloidal angle that takes into account the helical deformation of the magnetic axis. All the quantities plotted in Fig. 9 exhibit a helical modulation, with the same periodicity $(m=1,n=7)$ as the dominant mode. The ambipolar electric field $E_r$ is also dependent of the edge magnetic field (Fig. 9-e). Such behaviour can be compared with the high density regime,
where the edge magnetic perturbation features a $m=0$, $n=1$ periodicity and also modulates $E_r$ [43]. This can be an indication that the phase relation between magnetic perturbation and ambipolar field depends on collisionality and could help in understanding the different impact of RMP on ELM mitigation at different collisionalities.

7. Resistive Wall Mode studies

Understanding the physics of RWM’s and of their active control is a key topic for the $Q=5$ target of ITER and in general for advanced tokamak scenarios [45]. The research on RWM physics and active stabilization in RFX-mod has progressed both in the RFP and tokamak configuration (see Sect. 8). A dynamic model has been developed to integrate the plasma response in the presence of active and passive conducting structures (CARMa model) and a complete representation of the control system [46], including in the plasma response a large spectrum of RWMs with $\text{abs}(n)=2, 3, 4, 5, 6$ [47]. This is important to analyse the effect of reducing the number of control coils since it allows the simultaneous study of modes, which could be amplified by the low $n$ order sidebands, produced by the reduced set through Resonant Field Amplification. To investigate the reliability of the model, dedicated experiments were run generating robustly unstable mode whose growth rates are compared with those of the model. An example of the validation test is given in Fig. 10-A, where the evolution of the harmonic $m=1$, $n=3$ is shown. A negative gain $K_p=-500$ in the purely proportional controller was applied at $t=30$ ms and a clearly exponential growth can be appreciated with an estimated growth rate $\gamma=45$ s$^{-1}$, in good agreement with the model prediction of two unstable modes ($\gamma_1=46.3$ s$^{-1}$, $\gamma_2=46.8$ s$^{-1}$) with a dominant $m=1$, $n=3$ harmonic content as shown in Fig. 10-B. The influence on RWM control of different sets of active coils – which in RFX-mod can be by purpose downgraded starting from full coverage – has been studied [48].

RWM modelling [49,50] shows that RWM can be fully suppressed by kinetic effects in high beta RFP plasmas, with toroidal rotation frequency comparable to the ion acoustic frequency, much below the prediction of the previous fluid theory (which is in the range of the Alfvén frequency). Moreover, in-depth comparison of the kinetic physics on the RWM stabilization in the two configurations have been performed. The results demonstrate the significant role of magnetic configurations (tokamak vs. RFP) on the kinetic physics of the MHD mode.

8. Tokamak operation in RFX-mod

RFX has been run as a low current ($\approx 150$ kA), circular cross section, ohmic Tokamak with discharge duration up to one second. The main goals were to exploit the active control system directly in the tokamak configuration and to explore basic problems on transport and turbulence (comparing RFP and Tokamak behavior in the same device).
A breakthrough has been the stable operation at $q_{\text{edge}}=1.8$. Low $q$ scenarios are indeed an unexplored territory for tokamak, due to the stability issues posed by the (2,1) kink. Nonetheless, this region may be attractive as it allows for operation at high current and the fusion gain scale as $q_{95}^{-2}$. Experiments in RFX-mod have shown that while in absence of active control the (2,1) current driven RWM grows leading to a disruption with $q_{\text{edge}}>2$, when the feedback control is applied the mode is suppressed for the whole pulse duration at $q_{\text{edge}}=1.8$ (Fig. 11). An important finding is that the mode control is successful only if the aliasing of the sidebands harmonic generated by the feedback coils are subtracted from the radial field measurements (Clean mode Control, CMC technique) [12]. This demonstrates that CMC is the most effective way to use radial sensors for feedback control. Recently this experiment has been performed in DIII-D in a joint collaboration with RFX. Preliminary results in DIII-D indicate that a $q_{95}<2$ plasma can be produced or about 0.4 s at $I_p=1.7$MA with active control of the (2,1) RWM.

In RFX the low-$q$ control experiment has been performed also downgrading the active coil system from the full set of 192 down to 6. It has been found that also with 6 coils only the (2,1) mode can be controlled. Feedback-controlled helical boundary conditions, exploiting an algorithm similar to one developed to control helical RFP states, has been also applied to tokamak plasmas with $q(a)<2$. Allowing a finite (2,1) helical perturbation at the plasma edge has been found to mitigate sawteeth. Nonlinear MHD simulations show that this effect is likely due to the nonlinear coupling between the (1,1) internal kink and the (2,1) external kink. Such a coupling has the effect to reduce the amplitude and increase the frequency of sawtooth crashes, as show in Fig. 12. This effect was observed to occur spontaneously also in other tokamaks [51]. Here we propose to control the external kink and exploit this coupling effect to tailor sawteeth, as done in RFX-mod. This new approach seems rather robust and may find applications also to larger tokamaks. The flexibility of the feedback system has also allowed the study of the effect on the plasma flow of resonant and non-resonant perturbations. As the (2,1) mode amplitude is allowed to grow in a controlled way the toroidal plasma rotation is observed to slow down. Above a certain threshold (2,1) amplitude, the flow inverts its sign and starts rotating in the co-$I_p$ direction, therefore reversing from counter-$I_p$ direction (Fig. 13). This effect has been interpreted as a combination of two effects: a Neoclassical Torque Viscosity (NTV) and a stochastic torque due to the edge ambipolar electric field, both depending on the amplitude of the magnetic perturbation, as shown in Fig. 13.
RFX-mod offers the opportunity to study the contribution of coherent structures to the transport of particles and energy at the plasma edge, where large gradients develop, both in RFP and Tokamak configurations [52]. Particularly interesting are the magnetic field-aligned filamentary plasma structures with direct measurement of associated parallel current density and vorticity. Similar current carrying filamentary structures are found in ASDEX Upgrade [53] in type I ELMs events. A better knowledge of their characteristics could yield ideas for ELM suppression or mitigation. The origin of such structures is different in RFP and Tokamak: in the RFP they have a drift kinetic Alfven origin, while in Tokamak configuration they are related to small scale current filaments. Despite the different driving mechanism, and comparing RFX data with similar measurements performed in the Stellarator TJ-II and in TORPEX, filamentary structures share similar characteristics and dependences on global parameters in all the configurations. An example is given in Fig. 14.

The possibility of producing non-circular plasmas and thus of increasing the relevance of MHD control exercises in tokamak configuration has also been explored and a high triangularity plasma with double x-point has been produced (Fig. 15). The aim in establishing a double or single null configuration is on the one hand the extension of the study of low q regimes to non circular shapes and on the other hand the achievement of an ohmic H mode, which would open the way to further important studies such as ELM’s control.

9. RFX-mod feedback control system upgrade

The real-time control system of RFX-mod, in operation since 2005, was originally designed with the primary goal of controlling RWMs with the Virtual Shell algorithm. Later, mitigation of Tearing Modes with the Clean Mode Control based on the estimated radial field at the plasma edge [54] was found to require more complex algorithms and three times more control signals than originally designed. The increased requirements limited the cycle frequency to 2.5kHz with an overall latency of 2.5 ms (including the latency due to the digital controller of the power supply units). As predicted by the RFXlocking code, latency increase does not favour efficient control: the reduction of the latency of the system is in fact predicted to bring the edge radial field nearer to the ideal shell limit. Moreover further reduction of latency is expected by delivering voltage references instead of current references to power supply units.

To enhance computing power and reduce system latency, a major upgrade of the system has been designed [55] based on a new architecture. The central component is a Linux-based multicore server, where individual cores replace the VME computers. The new architecture merges into one server both the axisymmetric controllers (horizontal equilibrium, toroidal field and plasma current) and the MHD controller, allowing the latter to implement algorithms taking into account axisymmetric quantities. The server is connected to 4 PXI racks via fibre-optics based bus extenders. A PCIe port is dedicated to each bus extenders, each supervised by a separate core. In the complete project four cores carry out the operations performed by the VME processors supervising data acquisition and pre-elaboration, and four more cores are dedicated to the generation of the reference waveforms, thus employing in total 8 cores for I/O management. As a first step, an intermediate version of the new hardware architecture has been implemented with 3 of the previously used VME processors to acquire raw data and to be sent to the multi-core server. The system is supervised by MARTe, a
software framework for real-time applications written in C++, developed at JET and currently used for the JET vertical stabilization and in other fusion devices [56].

The first results are encouraging, showing that a frequency cycle of 5 kHz with a reduced latency (0.35-0.55 ms) has been achieved. Computation time is reduced. In the old system, where the more time consuming elaboration was the clean mode control, it was possible to apply the cleaning to only 20-30 harmonics within the cycle time. In this new system, the same algorithm, is performed in 100-150 µs, well below the 200-400 µs cycle time. This indicates that in principle complete Clean Virtual Shell experiments will be allowed.

10. Conclusions and outlook
These are challenging times for the international fusion programme. The strong commitment to build ITER within cost and time has to proceed together with a robust and visionary fusion science and technology accompanying program, which is key to lay the foundation of ITER exploitation and to achieve fusion power production before the middle of this century. Aware of these ambitious targets, RFX-mod has reacted to streamline its fusion science program to meet the new challenges exploiting its flexibility and its diversity.

The results presented in this paper confirm that not only helical states open a new path to assess the possibility of exploiting the RFP as a low-applied field fusion configuration alternative to the tokamak, but also that the development of tools for performance optimization (like wall-conditioning, first wall material choice, plasma control) is fully synergistic with the tokamak strategy. In addition, the in-depth investigation of helical states has made RFX-mod a key player in the three-dimensional physics effort. This has clearly opened a natural partnership with the stellarator community – now arrived to the point where the same modelling tools are used and benchmarked in the two configurations; and, in addition, has made RFX-mod an important contributor to the more general effort on three-dimensional physics also thanks to it state-of-the-art MHD stability control system, which allows to tailor the edge magnetic field. Last but not least, RFX-mod has contributed to the investigation of key open issues for magnetic confinement, like turbulence-driven transport, MHD stability, density limit, flow transport, by covering with its data regions of the parameter space otherwise unexplored. RFX future program will benefit from hardware upgrades, as that of the feedback system described in this paper.

These results – and the opportunity of new contributions to the international fusion program, also deriving from the possibility of tokamak and RFP operation in the same device – form the basis for an ambitious experimental program in support of ITER and of the progress of fusion physicists and ideal to train the next fusion science generation of fusion engineers and physicists.

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